

TEMPERATURE RISE FOR SPRING-LOADED PHASE CHANGE DEVICES

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ABSTRACT

Solid-to-liquid phase change materials (PCM) that may find use on planetary probes are examined. In this application, the PCM will perform only through the melting cycle to postpone the overheating of equipment within the probe. One way to minimize temperature rise is to maintain "solid phase contact melting". Resulting flow conditions in the liquid PCM film and temperature rise across the film are derived. The significance of the resulting equations, and ways suggested by them to reduce temperature rise, are discussed. The meager experimental data available is compared to results calculated by the equations.

NOMENCLATURE

d	Groove width
F	Force on solid PCM
g	Gravitational constant
ΔH	PCM heat of fusion
k	Liquid PCM thermal conductivity
L	Maximum dimension of heated surface
n	Number of zones between grooves in heated surface
P	Pressure in liquid PCM at ϕ
PCM	Phase change material
p	Pressure in liquid PCM at x
\bar{p}	Pressure on solid PCM
∇p	Pressure gradient in liquid PCM
q	Heat flux \perp heated surface
\bar{q}	Average heat flux \perp heated surface
T	Heated surface temperature
T_m	PCM fusion temperature
ΔT	Temperature difference between heated surface and solid PCM
V	Mean liquid PCM exit velocity
v	Mean liquid PCM velocity at x
∇v	Velocity gradient in liquid PCM
W	Minimum dimension of heated surface
x	Coordinate in the plane of the heated surface with origin at ϕ and parallel the minimum dimension
y	Liquid film thickness \perp heated surface
μ	Liquid PCM dynamic viscosity
ρ	Liquid PCM density
ρ_s	Solid PCM density

INTRODUCTION

Solid-to-liquid phase change materials (PCM) have been used since pre-historic times for temperature control, but only recently have they been applied to high technology systems. They have found use on the Lunar Rover and on Skylab, and probably will find use on planetary probes (see ref. 1). For the last application, the PCM will be called upon to perform only through the melting cycle to postpone the overheating of certain vulnerable equipment within the probe.

A container, enclosing a PCM, and comprising with it a phase change device, receives heat from the protected equipment, and melting begins at the fusion temperature. However, only the melting interface between liquid and solid PCM remains at the fusion temperature. All other parts closer to the heat source — liquid PCM, structure and the protected equipment — rise in temperature to maintain the necessary gradients for transfer of the heat. As the liquid PCM is typically a poor thermal conductor, means are often added to the device to minimize the thickness of liquid PCM and increase the area through which the heat must be transferred. Metal fins, honeycomb fillers and heat pipes have all been considered as means for enhancing heat transfer. One of

the most simple and effective means, at least for a device intended only for one melting cycle, is to maintain what has been called "solid phase contact melting". Of course, contact of solid PCM with the heated surface is not maintained at all, but the film of liquid PCM is dramatically reduced in thickness, and that is the desired effect.

Spring-loading of the solid PCM against the heated surface is only one of numerous ways of applying the necessary force. Motor drive, solenoid, pneumatic, hydraulic, vapor pressure, phase change expansion, thermal expansion, gravity or even inertial designs might all be competitive in certain applications. The following analysis is independent of the means of applying force.

ANALYSIS

Consider a rigid solid PCM inside a device of unspecified depth and of rectangular cross section parallel to the heated surface. The flat heated surface matches the device in area, being much longer than it is wide. A constant heat input is supplied to the heated surface. Specific heats of the solid and liquid PCM and structure will be neglected in comparison to the latent heat of fusion of the PCM. Spring-loading forces the solid PCM to move toward the heated surface, displacing the liquid PCM directly to the long edges of the heated surface. This, then, is a two-dimensional model of PCM melting, with heat flow in the direction perpendicular to the heated surface and liquid PCM flow parallel to the minimum dimension of the heated surface. See Figure 1.

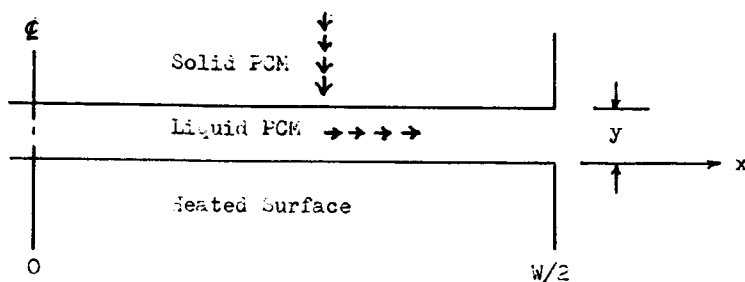


Figure 1. Phase Change Device Model

Because the solid PCM is rigid, no deformation of the solid PCM will occur. It moves as a body toward the heated surface. The rate of melting must be equal everywhere on its face. Its temperature is uniform at T_m , while the heated surface temperature is T , so ΔT from heated surface to solid PCM is equal everywhere. The heat flux at any point, if conduction dominates, is

$$Q = k \Delta T / y \quad (1)$$

Because the melting rate is uniform, and k and ΔT are uniform, y itself will be constant. The conclusion that the film of liquid PCM has a constant thickness makes an analytical treatment very convenient.

It should be noted that the constant film thickness between solid blocks of constant temperature is a very stable configuration. Perturbations to the film thickness cause local changes of opposite sign to the heat flux, a sort of negative feedback, which tend to tend to restore the quasi-equilibrium state.

The rate of motion of solid PCM will be $k \Delta T / y \rho_s \Delta H$, and rate of liquid volume production per unit area will be $k \Delta T / y \rho \Delta H$. Since all liquid PCM must travel in the x direction, the mean velocity must increase linearly from zero at the centerline of the heated surface to a maximum value at the edge. Flow will be laminar (justifying the conduction model), with plane parallel boundaries. For such a case,

$$-\nabla p = 12 \mu v / y^2 \quad (2)$$

Pressure will be its maximum value at the centerline, less the accumulated pressure drop:

$$\begin{aligned} p &= P - \int_0^x -\nabla p \, dx, \\ &= P - \int_0^x (12 \mu v / y^2) \, dx, \\ &= P - (12 \mu / y^2) \int_0^x v (2x / W) \, dx, \\ &= P - 12 \mu v x^2 / y^2 W \end{aligned}$$

Since $p = 0$ at $x = W/2$, $P = 12 \mu V (W/2)^2 / y^2 W$. Thus also $p = 12 \mu V [(W/2)^2 - x^2] / y^2 W$. All of the above illustrates in Figure 2.

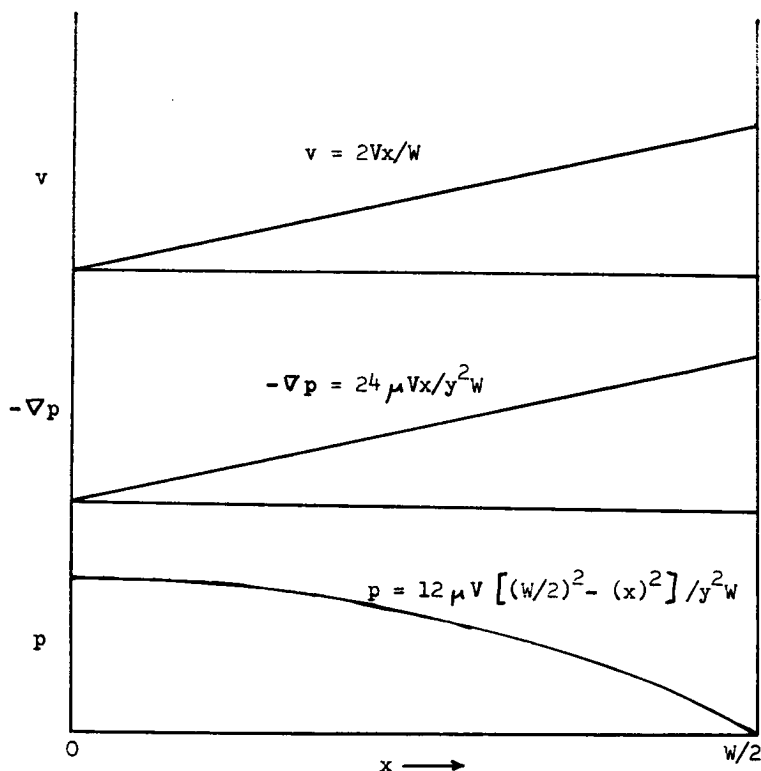


Figure 2. Velocity, Pressure Gradient and Pressure

Equation 2 is not strictly valid for this case because there is acceleration. Strictly speaking,

$$-\nabla p = 12 \mu v / y^2 + \rho \nabla v^2 / 2g, \text{ and}$$

$$p = 12 \mu V [(W/2)^2 - x^2] / y^2 W - \rho v^2 / 2g$$

It can be shown, however, that the second term is several orders of magnitude smaller than the first for all presently conceived PCM and device configurations. The temperature dependence of viscosity has been neglected in the first term (see ref. 2).

The pressure distribution is parabolic, and centerline pressure is $3 \mu VW / y^2$, so mean pressure is $2 \mu VW / y^2$. This can be equated to the force exerted on the solid PCM, divided by the area of that solid:

$$F / LW = 2 \mu VW / y^2, \text{ or}$$

$$\bar{p} = \frac{2 \mu VW}{y^2} \quad (3)$$

Also, since all liquid PCM is discharged at the edges:

$$k \Delta T W / 2 y \rho \Delta H = V y, \text{ or}$$

$$V = \frac{k \Delta T W}{2 y^2 \rho \Delta H} \quad (4)$$

From Equations 3 and 4,

$$\frac{\bar{p}}{2 \mu} y^2 = \frac{k \Delta T W}{2 y^2 \rho \Delta H}, \text{ or}$$

$$y^4 = \frac{k \mu \Delta T W^2}{\bar{p} \rho \Delta H} \quad (5)$$

From Equations 1 and 5,

$$q^4 = k^4 \Delta T^4 / y^4, \text{ or}$$

$$q^4 = k^4 \Delta T^4 \bar{p} \rho \Delta H / k \mu \Delta T W^2$$

Rearranging,

$$\Delta T = q^{4/3} W^{2/3} \mu^{1/3} / k^{1/3} \bar{p}^{1/3} (\rho \Delta H)^{1/3} \quad (6)$$

Equation 6 also gives scaling laws for devices for which this model is sufficiently approximate. ΔT is raised by increased heat flux, heated surface size and liquid PCM viscosity. All three factors increase the liquid PCM film thickness. ΔT is lowered by increased liquid PCM thermal conductivity more effectively than by increased loading on the PCM or increased PCM volumetric latent heat. However, it is evident that one could double the force and halve the size, and still retain the same ΔT at twice the heat flux with a given PCM. Furthermore, it is quite evident that reducing flux by increasing size will be only marginally effective in reducing ΔT . A much better approach would be to reduce effective size by cutting canals in the face of the heated surface to furnish easy paths to the edge. Recommendations on the proper means of fabricating the canals are discussed below.

Other results have been obtained. For a fully deformable

PCM with ∇p assumed as $4F/LW$ and using $q = (2/W) \int_0^{W/2} (K \Delta T / y) dx$, one gets

$$y^4 = 4 k \mu \Delta T W \pi / \bar{p} \rho \Delta H, \text{ and}$$

$$\Delta T = 0.86 \bar{q}^{4/3} W^{2/3} \mu^{1/3} / k \bar{p}^{1/3} (\rho \Delta H)^{1/3} \quad (7)$$

For a rigid cylindrical PCM heated on one circular end, with diameter D , one gets

$$y^4 = (3/8) k D^2 \mu \Delta T / \bar{p} \rho \Delta H, \text{ and}$$

$$\Delta T = 0.72 \bar{q}^{4/3} D^{2/3} \mu^{1/3} / k \bar{p}^{1/3} (\rho \Delta H)^{1/3} \quad (8)$$

DESIGN

It is suggested above that improving the drainage of melted PCM from the heated surface, in this particular kind of phase change device, reduces the amount of temperature rise of that surface above the PCM melting temperature for a given heat flux. In this way, the device can be made to approach more closely the ideal of a constant-temperature heat sink.

The analysis indicates that ΔT is proportional to the two-thirds power of the heated surface characteristic dimension. This is contingent on there being efficient drainage of the liquid PCM from the edges of the heated surface without appreciable back pressure. If the heated surface can be divided into (n) separately drained regions by $(n-1)$ equally spaced grooves, then ΔT will be reduced by a factor of $(n)^{-2/3}$. Thus, seven grooves would reduce ΔT to $1/4$ its former value. Shallow saw cuts in the face of the heated surface would suffice as grooves. Flow of the liquid PCM in these grooves would not require any significant part of the pressure drop, providing these grooves are large enough to be conveniently fabricated (equal to or larger than about 1 mm) and providing that larger cross grooves drain these grooves at frequent enough intervals. Figure 3 shows an arrangement of grooves on a heated surface which would reduce ΔT by nearly 75%.

More grooves would reduce ΔT even more, but the surface would be all grooves. In Figure 3, 8.3% of the area is lost for efficient transfer of the heat flux to solid PCM. If the loss of area is conservatively treated as an increase in heat flux, then heat flux is increased by a factor of $[1-(n-1)d/W]^{-1}$, neglecting cross grooves, or about $[1-(n+1)d/W]^{-1}$ with them. Here d is the groove width, and W is the heated surface width. The characteristic dimension is reduced also by a factor of $[1-nd/W]$. As ΔT is proportional to the four-thirds power of heat flux, minimum ΔT will be obtained by minimizing the expression $\Delta T_2 / \Delta T_1 = [n / (1-nd/W)]^{-2/3} [1-(n+1)d/W]^{-4/3}$.

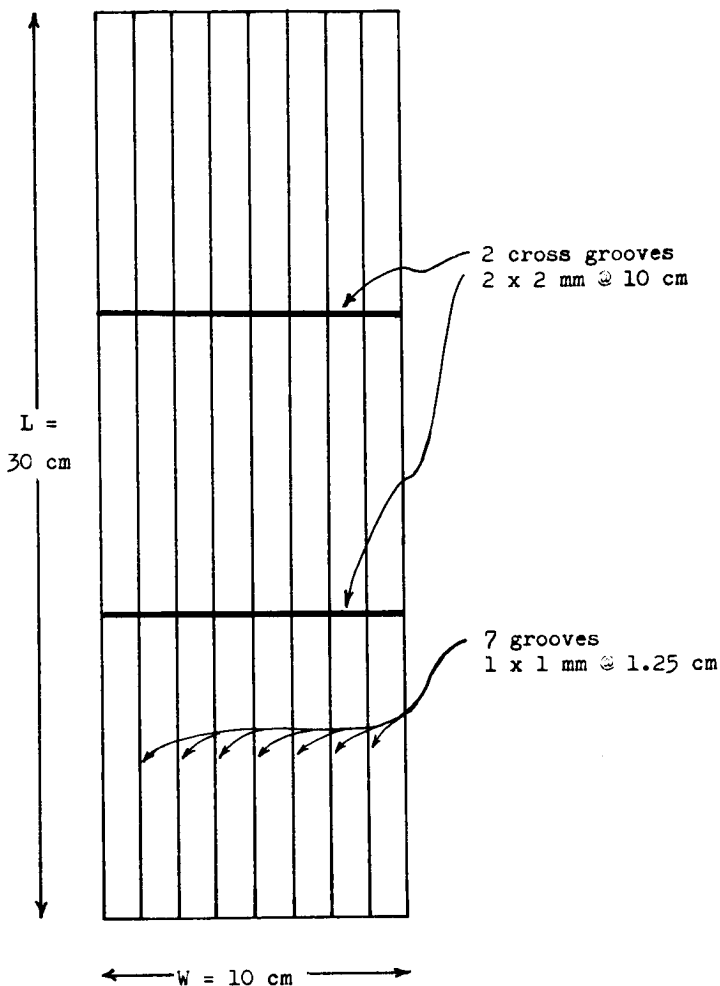


Figure 3. Typical Heated Surface Groove Pattern

ΔT_2 and ΔT_1 are temperature rises with and without the grooves. The ratio can analytically be determined to be a minimum when $n \approx W/2d$; that is, when half of the area is taken up with grooves. The expression for $\Delta T_2 / \Delta T_1$ is plotted in Figure 4, for the dimensions given in Figure 3. The difference between the $\Delta T_2 / \Delta T_1$ value and that for $(n)^{-2/3}$ represents the counter effect of area loss.

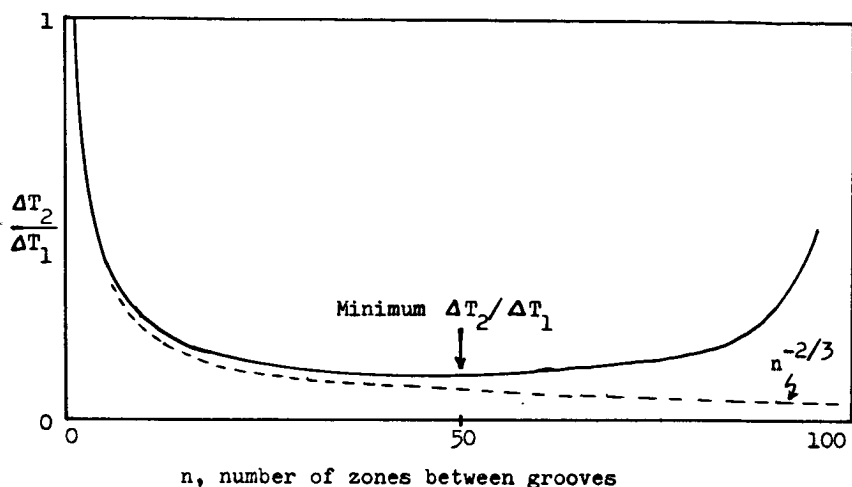


Figure 4. Effect of Grooves on Temperature

CORRELATIONS

There is at this time no data from spring-loaded devices with heated surfaces sufficiently long and narrow to approximate the model of Equation 6. Two devices have been operated with the same loaded PCM, octadecane (see refs. 3 and 4). One device had a heated surface 7.3 x 15.1 cm and was loaded with 25 lb. The other was 4.4 x 7.0 cm and was loaded manually, so that the applied force may have been in the neighborhood of 50 lb. The pressure ratio then may have been 25 / 7.3 (15.1) : 50 / 4.4 (7.0) or about 0.14. The ratio of heat fluxes imposed on the two devices was 1:1.73. Calculated ΔT ratio is

$$\begin{aligned} \Delta T_1 / \Delta T_2 &= (q_1 / q_2)^{4/3} (w_1 / w_2)^{2/3} (\bar{p}_1 / \bar{p}_2)^{-1/3} \\ &= (1/1.73)^{4/3} (7.3 / 4.4)^{2/3} (0.14)^{-1/3} \end{aligned}$$

$$= (0.48) (1.40) (1.92)$$

$$= 1.3$$

whereas measured ΔT ratio was $\frac{30}{3} = 10$. ΔT in the smaller device was somewhat larger than the model predicted, probably because of a thicker film due to appreciable increased viscosity of liquid in the film next to the melting interface. However, the larger device ΔT was very much larger than predicted, apparently due to reduced effective loading arising from appreciable back pressure in the liquid PCM at the edge of the heated surface. The larger device had a tighter fitting plunger exerting force on the solid PCM, which also was a deeper block than that in the smaller device. Increased viscosity was also undoubtedly at work, as suggested by the discrepancy between device heat capacity and total heat absorbed. PCM Volume $\times \rho \Delta H$ was greater than $q \times \text{area} \times \text{time}$ until the heated surface started continuously rising in temperature, implying in-complete melting of the block of solid PCM. If fragments of solid PCM were being carried away in the melt, then viscosity would be much higher than the value for a pure liquid PCM. Additional details of the calculation are shown in Table 1, which also lists data for the first device with another PCM.

Table 1. Sample ΔT Calculation

Device	Small	Large	Large
PCM (Properties from ref. 5)	Octadecane*	Octadecane*	LiNO ₃ · 3H ₂ O**
q, watts/cm ²	0.85	0.49	0.49
W, cm	4.4	7.3	7.3
$\bar{\rho}$, gm/cm ²	~ 736	103	103
Calculated y, cm	0.0015	0.0033	0.0022
V, cm/sec	6.7	2.9	1.9
Reynold's No.	≤ 0.3	≤ 0.3	≤ 0.2
ΔT , K	0.8	1.1	0.2
Measured ΔT , K	~ 3	30	~ 25-13***

CONCLUSIONS

The most that can be said is that Equation 6 remains unconfirmed by experiment. New experiments of proper design, appreciating the influences of the parameters in Equation 6, are needed to make any judgement of its validity. Even if the calculation of ΔT must be made with adjusted physical property data (such as viscosity) to match the experiments, the use of the equation as a scaling law may still be valid. At the very least, it suggests that there is considerable improvement available in the design of real devices.

REFERENCES

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*A viscosity value for a few degrees above T_m was used.

**A viscosity value for water near the PCM melting temperature was used.

***This ΔT was decreasing with time, indicating what may be explained as a decreasing backpressure effect.